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CDF

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SINGLE TOP PRODUCTION AND $M_{t\bar{t}}$

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Single top production provides opportunities for studying the charged-current weak interaction of the top quark. The $t\bar{t}$ invariant mass spectrum $M_{t\bar{t}}$ enables the search for non-standard model $t\bar{t}$ resonance states. These two topics have motivated new developments in top quark related analyses at Fermilab Tevatron. This presentation reports the current single top and $M_{t\bar{t}}$ analysis methods and the corresponding results from the collider Run I data collected by the CDF and DØ experiment. We conclude with the prospects for these studies in the upcoming collider Run II

1 Introduction

Since the top quark was discovered, both CDF and DØ experiment have been pursuing further searches in the top signal channel for new physics. With the available data collected in Run I, both experiments conducted searches for evidence of singly produced top quarks, and examined various kinematic variable distributions within the $t\bar{t}$ system. While the single top search analysis results from DØ is not available at this time, we report the recent single top results from CDF. We then outline the recent progress in kinematic studies in the $t\bar{t}$ system at both experiments, and contemplate on the potentials for Run II.

2 Single Top Searches at CDF

2.1 Motivation

Standard model predicts the production of single top quarks. Studies in the single top channels can provide cross-checks for the top quark mass measurements, due to the cleaner event structure with less multi-jet combinatoric complications. In addition, single tops also offer a good testing ground for probing the charged-current interaction of the top quark at the $t - W - b$ vertex. The production cross section provides a good handle on top quark partial width $\Gamma(t \rightarrow Wb)$ and CKM matrix element V_{tb} . New physics beyond standard model can also be revealed by an anomalous single top production rate.

2.2 Search channels and event topology

In the Fermilab Tevatron collider environment, the dominant single top production processes are the **W gluon fusion** and **s-channel W^*** channels (figure 1), with theoretical predictions of the cross sections at about $\sigma = 1.7 pb$ and $\sigma = 0.7 pb$ respectively^{1,2}. The characteristics for the W gluon fusion channel are 1 hard b-jet from top decay and 1 soft b-jet (probably missing) and 1 light quark jet + W decay lepton and missing \cancel{E}_T . The data sample is W + 2 jets sample, with 1 b-tag (SECVTX or SLT). For s-channel W^* events, the signatures are 2 hard b-jets + W

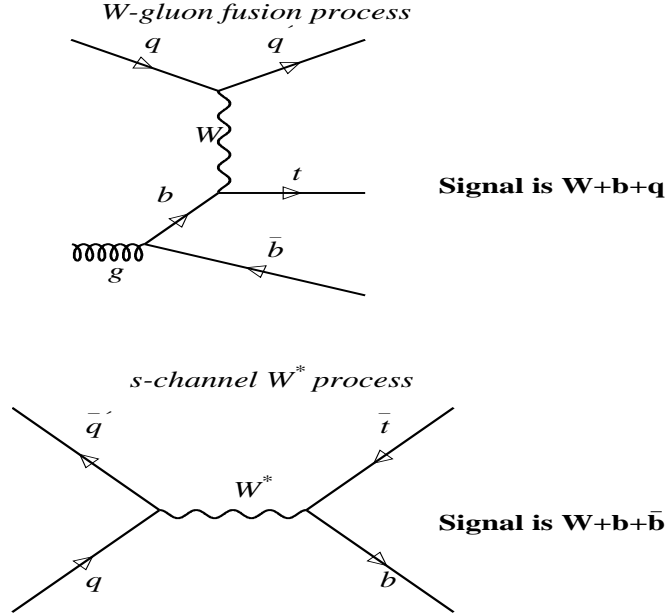


Figure 1. Dominant single top production processes.

decay lepton and missing \cancel{E}_T , and we searched for them in the $W + 2$ jets sample, with ≥ 1 b-tags (SECVTX or SLT).

2.3 Selection Cuts

The signatures for both types of events are similar, but s-channel W^* events tend to have two b-tagged jets. The event selection started with $W +$ jets data samples that passed the inclusive lepton trigger requirement from the $109 \pm 7 pb^{-1}$ data sample in Run 1, and were then required to pass the corresponding selection criteria. The CDF single top event selection cuts are similar to those applied in standard top lepton plus jet analysis. For the W gluon fusion sample, we required an isolated lepton with $E_T > 20$ GeV, missing $\cancel{E}_T > 20$ GeV, exactly two jets with $E_T > 15$ GeV and $|\eta| < 2$, 1 b-jet tag (SECVTX or SLT), and removal of di-lepton events. We also introduced an additional cut on reconstructed top mass window $145 < M_{l\nu b} < 205 GeV/c^2$ to improve S/B, with estimated efficiencies at 80% for signal, and 46% for background. There is also a need to remove doubly b-tagged events since W gluon signal events have only one b-jet in the two leading jets.

For the s-channel W^* sample, the cuts are similar to those applied in the W gluon fusion sample, but we required ≥ 1 b-jet tags, and no doubly-tagged event removal.

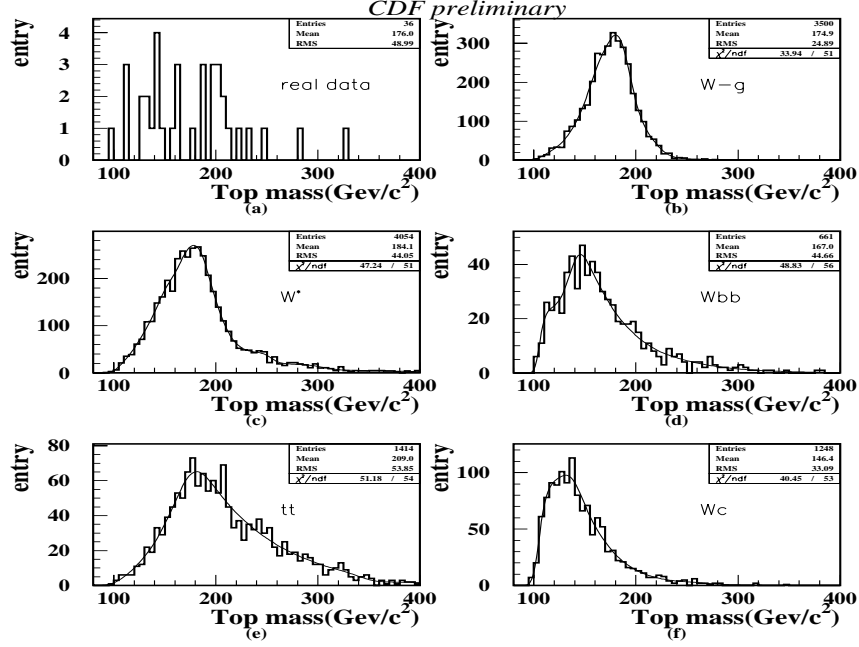


Figure 2. Reconstructed top mass distributions : (a) CDF data (b) W gluon MC (HERWIG) (c) W^* MC (HERWIG) (d) $Wb\bar{b}$ MC (VECBOS) (treated as main QCD background) (e) $t\bar{t}$ MC (HERWIG) (f) Wc MC (Pythia).

The reconstructed top mass distributions from various data and Monte Carlo event samples are shown in figure 2. The top mass window cut values are selected to give the best S/\sqrt{B} ratios.

2.4 Signal Acceptance from MC (HERWIG+QFL') Studies

The single top signal acceptance (convoluted with branching fractions) were studied with Monte Carlo data samples, including trigger and detector simulations. Table 1 summarizes for both single top channels.

After all the selection cuts applied, we found the following remaining event counts for the Run I data samples (normalized to $109pb^{-1}$) as summarized in tables 2 and 3.

2.5 Likelihood Fitting

From the Monte Carlo studies, we found that, in W gluon events, the pseudo-rapidity of the non-tagged light quark jet tends to be $+$ for t events and $-$ for \bar{t} events. As a result, the distribution of lepton charge times untagged jet pseudo-

Table 1. Single top acceptances and efficiencies

	s-channel W*	W-gluon fusion
$\sigma_{theory} \times \text{luminosity (events)}$	79.9	189 ± 13
W + 2 jet cut acceptance (%)	3.4	3.3 ± 0.6
SVX b-tag efficiency (%)	37.5	24.8 ± 2.0
SVX b-tagged events	1.0	1.6 ± 0.3
double b-tag efficiency (%)	8.8	0.5 ± 0.04
double b-tagged events	0.24	0.03 ± 0.01

Table 2. W gluon event sample surviving cuts.

QCD + W* background	10.8 ± 2.0
$t\bar{t}$ background	2.2 ± 0.6
Total background	13.0 ± 2.1
Wg signal	1.2 ± 2.0
Observed	15

Table 3. W* event sample surviving cuts.

QCD background	24 ± 4.5
$t\bar{t}$ background	5.7 ± 1.3
Wg signal	1.6 ± 0.3
W* signal	1.0 ± 0.3
Total	32.3 ± 4.7
Observed	42

rapidity is asymmetrical for W gluon single top events (figure 3). This distribution provides the handle for performing binned maximum likelihood fits in order to extract the signal fractions.

The resulting likelihood fit is shown in figure 4, and the extracted number of signal events is $N_s = 1.4^{+4.2}_{-3.4}$ with background constraint, and $N_s = 0.0^{+6.7}_{-0.0}$ without background constraint.

For the s-channel W* single top sample, we performed maximum likelihood fits on the reconstructed M_{top} distribution instead (figure 5). The extracted number of signal events is $N_s = 6.6^{+7.3}_{-6.5}$ with background constraint, and $N_s = 0.0^{+10.7}_{-0.0}$ without background constraint.

We estimated systematic uncertainties on the $Q \times \eta$ and reconstructed top mass distribution shapes and acceptances by pseudo experiments. Sources of uncertainties include initial state radiation (ISR), final state radiation (FSR), differences in parton distribution functions (PDFs), and background uncertainties. These systematics are included in the estimation for cross section upper limits.

2.6 Cross-section upper limits

Since the observed signal events as extracted from the likelihood fits are consistent with zero within error margins for both W gluon and W* channels, we proceed to set the cross-section upper limits. To start with, we calculated the likelihood

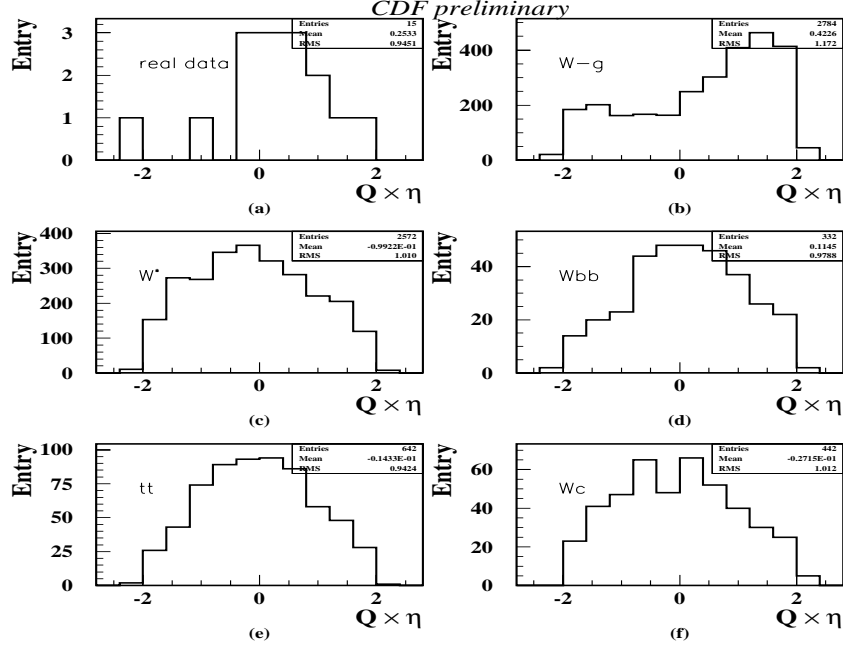


Figure 3. Distributions of lepton charge times untagged jet pseudo-rapidity for W gluon events.

$L(X)$ of given signal fractions by maximizing L with respect to $n_{t\bar{t}}$ and n_{QCD} . This resulted in the $L(X)$ curve and we obtained the cross-section upper limit at 95% CL without systematic uncertainties. To include the effects of the systematic uncertainties, we smear the $L(x)$ on the shape of the $Q \times \eta$ distribution and signal acceptance. We thus obtained the modified $L'(x)$ curves for both channels. The extracted cross section limits with systematic uncertainties included are found to be 15.4 pb at 95% CL for the W gluon channel, and 15.8 pb at 95% CL for the W* channel.

2.7 Improvements for Run II

During the upcoming collider Run II, we expect to substantially improve the single top event yields, detector acceptances, and selection cut efficiencies at both experiments. The major modifications include increased integrated luminosity (by a factor of 20) at the Tevatron, cross section increases (by 40% for top production, 12% for QCD background). Both experiments are undergoing major detector upgrades to improve detection capabilities and increase geometrical acceptance. (CDF : SVXII, ISL, COT, Plug Calorimeter, Muon, etc. ; DØ: new silicon and fiber tracker, etc.) The S/B ratios are expected to improve from ($S/B = 1 : 12, S/\sqrt{B} = 0.5$) in Run

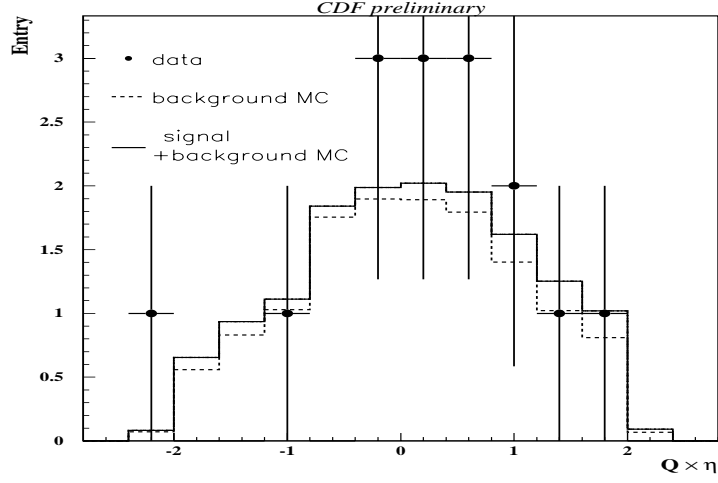


Figure 4. W gluon channel, binned maximum likelihood fits.

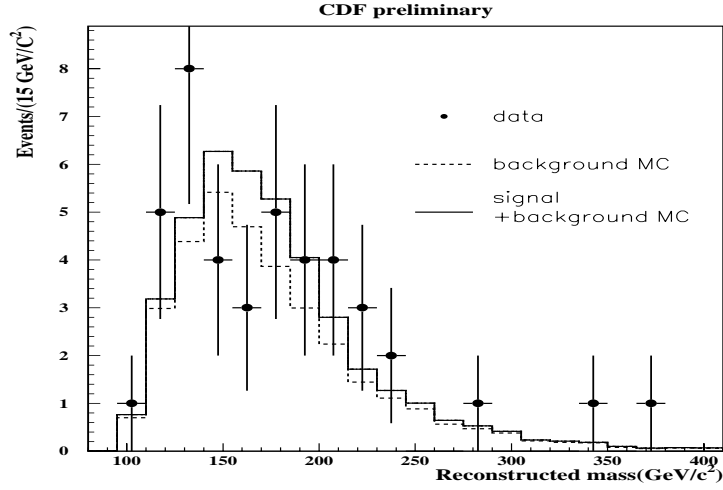


Figure 5. W* channel, binned maximum likelihood fits.

I to ($S/B = 1 : 10$, $S/\sqrt{B} = 3.8$) in Run II. Both experiments are also planning to implement new or improved cuts, including jet E_t , η , H_t , and top mass window cuts.

Tables 4 and 5 shows the CDF Run 2 estimation of single top "tagged W+2 jets" acceptance and yield. The center of mass energy was set at $\sqrt{s} = 2.0$ TeV, and latest theoretical calculations on σ_{Wg} , σ_{W^*} , $\sigma_{t\bar{t}}$ were used. The event yields

Table 4. Run II W gluon acceptance and yield.

Wg	Acceptance		Yield	
	Run 1B	Run 2	Run 1	Run 2
Produced			187	4900
W + 2 jets	3.3%	3.9%	6	190
W + 2 jets + $\geq 1 b - tag$	1%	1.9%	2	90

Table 5. Run II W* acceptance and yield.

W*	Acceptance		Yield	
	Run 1B	Run 2	Run 1	Run 2
Produced			80	1800
W + 2 jets	3.5%	4.2%	3	70
W + 2 jets + $\geq 1 b - tag$	1.5%	2.7%	1	50

were scaled by Run 2 detector acceptance improvements, for the total estimated data size of $2fb^{-1}$.

2.8 Single Top Perspectives

Within Run I data, single top studies were able to set cross section upper limits in both W gluon and W* channels (CDF). With the projected higher event yield and better S/B ratios in Run II, single top evidence is expected to be identified. Further studies will provide deeper understanding of the t-W-b vertex and obtain better measurements on the top partial width $\Gamma(t \rightarrow W + b)$.

3 $M_{t\bar{t}}$ and Kinematic Studies at CDF and DØ

3.1 Motivation

Some beyond standard model theoretical frameworks, like topcolor assisted technicolor, predict the existence of heavy objects (Z' or top-gluons) which decay into $t\bar{t}$ pairs. CDF's published $t\bar{t}$ production cross section is in excess of the standard model prediction, which potentially can be explained by the existence of heavy $t\bar{t}$ condensates. Further refinement on $t\bar{t}$ production cross section measurement is in progress. In the meantime, one can start to search for the possibilities of non-standard model $t\bar{t}$ resonance states.

3.2 CDF $M_{t\bar{t}}$ Analysis

For event selection, the CDF $t\bar{t}$ kinematic studies used similar cuts to those in lepton + jet top mass and cross section analysis³. We required the events to have an isolated, high P_T lepton, 3 jets with $E_T > 15 GeV$, $|\eta| < 2.0$, a 4th jet with $E_T > 8 GeV$, $|\eta| < 2.4$, missing $\cancel{E}_T > 20 GeV$, and rejected events with invariant mass falling in the Z-mass window. For tagged samples, we required at least one SVX or SLT b-tag. For the untagged sample, we required no b-tags but the 4th jet must satisfy $E_T > 15 GeV$, $|\eta| < 2.0$.

We used various Monte Carlo event samples to study the characteristics of $X \rightarrow t\bar{t}$ events. For $t\bar{t}$, we used HERWIG with top mass set to $175 \text{ GeV}/c^2$. For non- $t\bar{t}$ W + jet QCD background, we used VECBOS. The non-standard model condensates, particularly Z' signals, were simulated using Pythia, with width at about 1.2% of $M_{Z'}$, and generated with $M_{Z'}$ set at 400, 500, 600, and $700 \text{ GeV}/c^2$.

There are various methods for determining $M_{t\bar{t}}$, and they all depend on the MINUIT mass fitting package. A crucial χ^2 variable is defined for each possible combinatoric combination and minimized by MINUIT. The one combination with the lowest χ^2 and satisfies the b-tagging information is chosen as the best combination for calculating $M_{t\bar{t}}$. The three methods for calculating $M_{t\bar{t}}$ are,

- *6-Body Mass Method* : Does not use the 4-momenta returned by the mass fitter, but simply calculate the invariant mass of the lepton, neutrino, and 4-jet system $M_{l\nu jjjj}$ instead. (using unfitted 4-momenta as measured in the detector. Top mass : constrained to be $175 \text{ GeV}/c^2$) when minimizing the χ^2 .
- *Unconstrained Method* : Uses the 4-momenta returned by the mass fitter, but with the top mass unconstrained when minimizing the χ^2 .
- *Constrained Method* : Uses the 4-momenta returned by the mass fitter, but with the top mass constrained to be $175 \text{ GeV}/c^2$ when minimizing the χ^2 .

The Constrained Method, while exhibiting unphysical excess at low $M_{t\bar{t}}$ (figure 6), provides the best resolving power at all pertinent Z' masses. We therefore choose the constrained method. Further cuts need to be considered for reducing the contribution of the unphysical region due to wrong jet configurations.

$M_{t\bar{t}}$ spectra for various wrong combinations have been studied to understand the excess at low $M_{t\bar{t}}$. If at least one b-jet is exchanged with the W-jet, $M_{t\bar{t}}$ tends to be measured too low. For such events, the unconstrained jjj and $l\nu j$ 3-body masses tend to be too high. This appeared to be an artifact of the constrained method. Therefore, further $M_{3\text{-body}}$ cut : $150 \text{ GeV}/c^2 < M_{l\nu j}^u, M_{jjj}^u < 200 \text{ GeV}/c^2$; and χ^2 cut : $\chi_c^2 < 50$ were established to reduce incorrect solutions and improve the shape of the $M_{t\bar{t}}$ spectrum.

From the Run I data sample of 109 pb^{-1} , we found 63 data events remained after cuts, and the $M_{t\bar{t}}$ spectrum is shown in figure 7. Systematic error estimations are currently underway. CDF aims to establish the cross section upper limits for generic objects decaying to $t\bar{t}$ in the mass range 400 to $700 \text{ GeV}/c^2$.

3.3 $D\bar{O}$ $M_{t\bar{t}}$ studies

$D\bar{O}$'s $t\bar{t}$ kinematic studies implemented selection cuts similar to the lepton + jet top mass analysis cuts. Primarily, the events are required to have an isolated electron or muon with $E_T > 20 \text{ GeV}$, $|\eta^e| < 2.0$ or $|\eta^\mu| < 1.7$, at least 4 jets with $E_T > 15 \text{ GeV}$, $|\eta^{jet}| < 2.0$, missing $\cancel{E}_T > 20 \text{ GeV}$, and rejected events which contain photons. There are also additional cuts for tagged muons.

Various kinematic quantities are derived from the data sample, with their distributions dependent on the kinematic fits. We studied the resulting distributions corresponding to the jet permutations with the smallest χ^2 values.

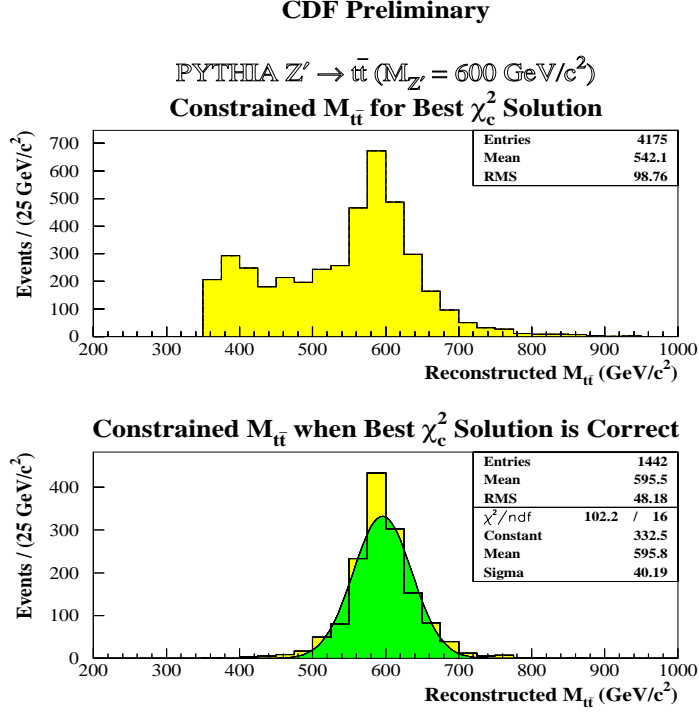


Figure 6. Invariant mass spectrum with the constrained method.

As examples, the resulting $M_{t\bar{t}}$ and $\eta_{t\bar{t}}$ (the difference in pseudorapidity between the two top quarks) distributions are shown in figures 8 and 9. The results from both 2C and 3C (with additional constraint that $m_t = 173.3 \text{ GeV}/c^2$) fits are indicated on the plots, as well as the Kolmogorov-Smirnov (K-S) probabilities resulting from the comparison between data and a mixture of $t\bar{t}$ and background models. The distributions of various kinematic variables show good agreement between data and standard model expectations.

3.4 $M_{t\bar{t}}$ Perspectives

While systematic errors are being studied for the kinematic variables in the $t\bar{t}$ system, work is also underway for estimating the cross section upper limits for beyond standard model $X \rightarrow t\bar{t}$ processes. For Run II, if no apparent excess found, we expect to be able to exclude the existence of non-standard model top quark condensates within various mass ranges.

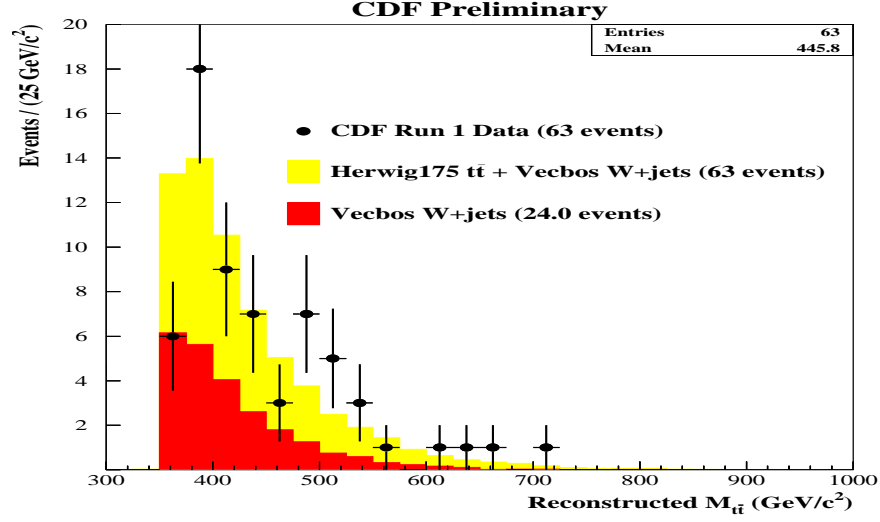


Figure 7. CDF reconstructed $t\bar{t}$ invariant mass spectrum from Run I data.

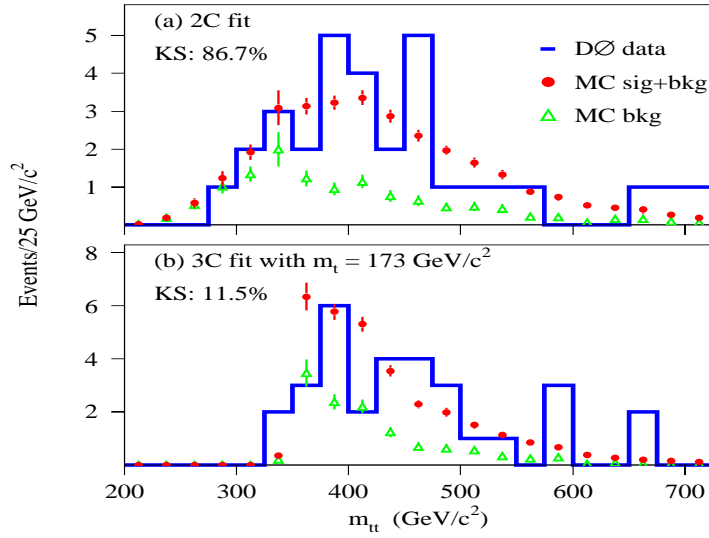


Figure 8. Invariant mass distribution of $D0\ t\bar{t}$ events from Run I data. The histogram is data, open triangles are expected background, and filled circles are expected signal + background. (a) 2C fit, (b) 3C fit with $m_{top} = 173.3\text{ GeV}/c^2$.

4 Summary

Single top searches have been conducted using available data from Fermilab collider Run I data. While there was no direct evidence for existence, CDF set the

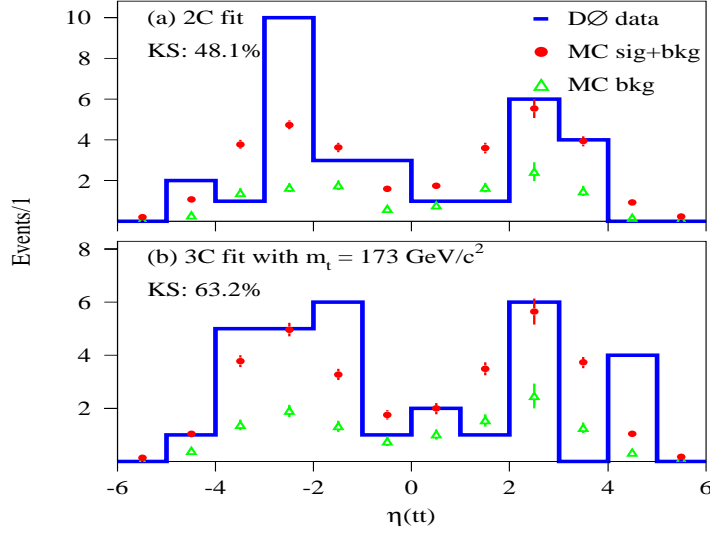


Figure 9. $t\bar{t}$ pseudorapidity difference distribution from DØ Run I data.

production cross section upper limits for both W gluon and W* channels. DØ and CDF also made further kinematic studies in the $t\bar{t}$ system, and the invariant mass spectra are consistent with standard model $t\bar{t}$ production plus backgrounds. With the substantially increased integrated luminosity in the upcoming Run II and improved detector acceptances and efficiencies, both experiments are looking forward to new physics opportunities in the single top and $X \rightarrow t\bar{t}$ channels.

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